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# Higgs Searches and Prospects at CDF

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## 1 Introduction

The Standard model of electroweak interactions (SM) has been extemely successful in describing interactions of elementary particles over the last decades. The Higgs scalar boson is one of the key elements of the SM: Higgs interactions with the other particles generate the particle masses and allow to keep the theory renormalizable at electroweak scale. All the particles predicted by the SM but the Higgs boson have already been observed experimentally and therefore search for the Higgs is one of the most important scientific goals for high energy physics. The current lower limit on the SM Higgs mass $M_H > 114.4\ GeV$ at 95% CL has been established by LEP experiments. In this paper we review CDF Run I results on Higgs searches including the Higgs bosons predicted by the minimal supersymetric extention of the Standard Model (MSSM) and discuss the Run II prospects.

## 2 SM Higgs Production at Hadron Colliders

Small production cross section poses a real challenge to the experimental searches of the Higgs boson. Shown in Fig.1(right) is the cross section for the SM Higgs production in $\mathrm{p\bar{p}}$ collisions for different elementary processes as calculated in [1]. The dominant mechanism is the gluon fusion $\mathrm{gg \to H}$ and for the Higgs mass of 120 GeV the corresponding cross section is about 0.7 pb. However the irreducible QCD background (gg, $\mathrm{q\bar{q} \to b\bar{b}}$ ) is too large to allow observation of Higgs signal in this channel. Because of this the most promising experimentally are the processes where Higgs is produced in association with the vector bosons W and Z - in these channels one could trigger on high-$\mathrm{P_t}$ leptons from the vector boson decays. The cross section of these processes is even smaller. As follows from Fig.1(left) for the same value of $\mathrm{M_H} = 120$ GeV $\sigma$ ( $\mathrm{p\bar{p} \to HW}$) is 0.16 pb, which has to be compared with the smallest measured so far cross section $\sigma$ ( $\mathrm{p\bar{p} \to t\bar{t}}$ ), which is about 5 pb.

Couplings of the Higgs boson to other particles are proportional to the particle masses and the phenomenology of Higgs decays depends strongly on the Higgs mass. Fig. 1 (right) shows dependence of different Higgs branching

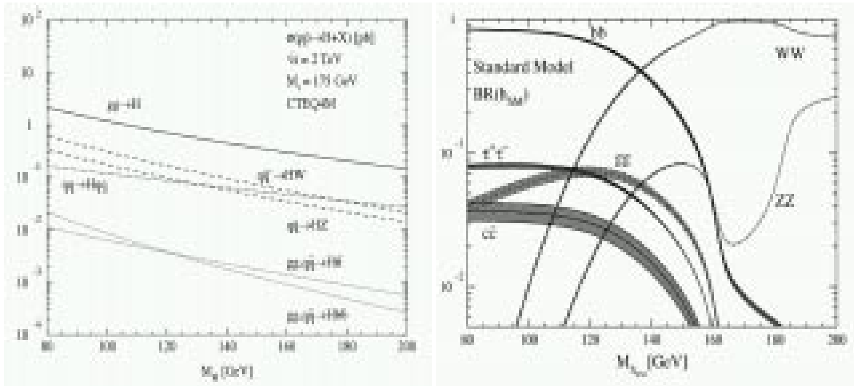


Figure 1. Left: cross section of the SM Higgs production [1], right: SM Higgs branching ratios as a function of Higgs mass

ratios on its mass. As one can see, in the mass reqion below 135 GeV Higgs decays are dominated by $H \rightarrow b\bar{b}$ channel. Above this mass the $H \rightarrow WW$ channel starts opening up and because of the large W-boson mass it quickly becomes the dominant one. When Higgs mass approaches 180 GeV $H \rightarrow ZZ$ channel starts competing with WW channel and its distinct experimental signature with 4 high-$P_t$ leptons makes it a strong preference in the mass region above 180 GeV.

### 2.1 CDF Run I searches for the light SM Higgs

In Run I CDF performed searches for SM Higgs boson in several channels. As the SM predictions for the Higgs production cross section are significantly below the level of the experimental sensitivity of Run I, in all the search channels the upper limits on the Higgs production cross were reported.

### 2.2 $l\nu\ b\bar{b}$ channel

The $p\bar{p} \rightarrow WH$ channel, where the SM Higgs boson is produced in association with the W-boson, provides the highest single channel search sensitivity. For Higgs masses of 100-140 GeV the cross section $\sigma(p\bar{p} \rightarrow WH)$ varies in the range of 0.3-0.1 pb, and triggering on high-$P_t$ leptons from W decays provides efficient trigger. CDF searched for the associative WH production requiring the trigger lepton to have $P_t$ >20 GeV and $|\eta|$<1 and 2 jets to have $E_t$ >15 GeV [3]. Having required only 1 out of 2 jets to be B-tagged ("single tag" sample), CDF found 36 events (22 with high-$P_t$ electron, 14 with high-$P_t$ muon) with the expected number of $30 \pm 5$ events. An alternative selection of events with both jets required to be B-tagged ("double tag" sample) resulted in a sample of 5 events with the SM expectation of 3.8 $\pm$ 0.7 events. Fig.2 (left) shows dijet mass distributions for both single tag and double tag samples.

### 2.3 ll $b\bar{b}$ channel

Signal in ll $b\bar{b}$ channel is very clean - 2 opposite sign high-$P_t$ leptons with the mass of Z-boson and 2 b-jets from Higgs boson decay. Using total statistics of 106 $pb^{-1}$ CDF experiment was looking for the events with 2 leptons (electrons or muons) with $P_t$ >20 GeV and 2 jets with $E_t$ >15 GeV/c. Requirement for one of the jets to have a B-tag reduced the event sample down to 5 (2 e-e 3 $\mu - \mu$) candidate events. SM backgrounds in this channel are dominated by $p\bar{p} \rightarrow Z\, b\bar{b}$ process and the predicted sum of all the SM backgrounds is 4 $\pm$ 1 events. The distribution for the dijet mass for ll $b\bar{b}$ candidate events is presented in Fig.2 (right).

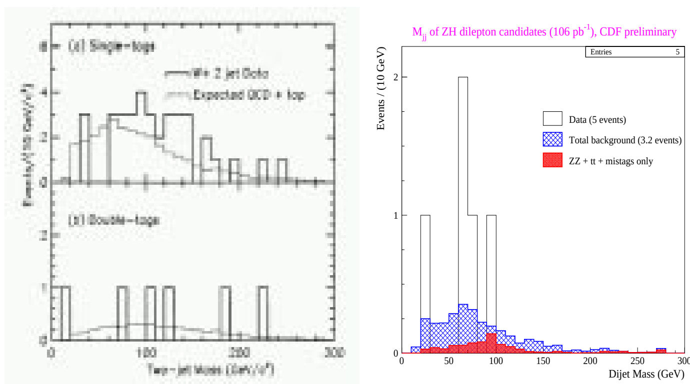


Figure 2. Left: dijet mass for Z $b\bar{b}$ candidate events, GeV. Right: dijet mass for W $b\bar{b}$ candidate events, GeV, single tag and double tag samples.

### 2.4 qq $b\bar{b}$ channel

CDF searched for the VH production in qq $b\bar{b}$ channel [4], assuming that a vector boson produced in association with the Higgs decays into $q\bar{q}$ pair. Large branching ratios of the $W/Z \rightarrow q\bar{q}$ generate a lot of interest to this channel, however irreducible qq $b\bar{b}$ background is also higher than in other VH final states. Selected events were required to have 4 jets with $E_t$ >15 GeV and $|\eta|$<2.1, 2 jets out of 4 had to have B-tags, $P_t$ of $b\bar{b}$ system was required to be >50 GeV. The number of events survived all the selections (589) is in good agreement with the expected background of 594 $\pm$ 30 events.

### 2.5 $\nu\nu$ $b\bar{b}$ channel

Search for Higgs production in $\nu\nu b\bar{b}$ channel performed by CDF exploits large branching ratio of $Z \rightarrow \nu\nu$. Selected events were required to have $\not{E}_T$>40 GeV and 2 jets with $E_t$ >15 GeV and $|\eta|$<2. 2 statistically independent samples - with only 1 B-tagged jet ("single tag") and with both jets B-tagged ("double tag") - were analysed. In the single tag sample we 40 events were observed and 43 ± 3 predicted, in the double tag sample 4 events were observed in agreement with the expectation of 4.9 ± 0.6 events.

### 2.6 Summary of the Run I SM Higgs Searches and Projections for Run II

Summary of Run I CDF searches for the SM Higgs boson in different channels is presented in table 1 and the combined CDF limits are shown in Fig.3.

| channel | L, $pb^{-1}$ | N(observed) | N(expected) |
|---|---|---|---|
| ll bb | 106 ± 4 | 5 | $4.0 \pm 1.0$ |
| $\nu\nu b\bar{b}$ | 87 ± 4 | 4 | $4.9 \pm 0.6$ |
| $l\nu$bb | 106 ± 4 | 6 | $3.8 \pm 0.7$ |
| $qq$bb | 87 ± 4 | 589 | $594 \pm 30$ |

**Table 1.** Summary of CDF Run I searches for the SM Higgs boson

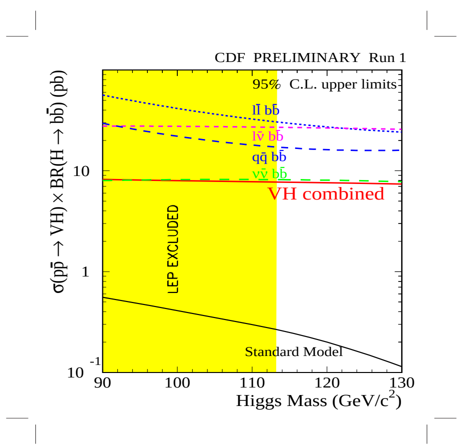


Fig.3. CDF limits on SM Higgs mass, all channels combined, 95% CL

For the SM Higgs mass of 130 GeV the combined CDF result can be expressed as follows

$$\sigma(p\bar{p} \rightarrow VH) \cdot BR(H \rightarrow b\bar{b}) < 7.4pb \ @ \ 95\%CL$$

As one can see from Fig. 2.6 in the mass range of 90 GeV to 130 GeV the SM prediction is 1 to 2 orders of magnitude below the level of Run I experimental sensitivity. The biggest improvement in Run II is expected to come from the significant increase in the integrated luminosity - 2 $fb^{-1}$ in Run IIa and 10-15 $fb^{-1}$ in Run IIb. Other sources include increase of the Tevatron cm energy up to 1.96 TeV, increase in B-tagging acceptance, improved resolution in impact parameter and improved jet energy resolution. Detailed study of the reach of 2 Tevatron experiments performed in [5] lead to the conclusion that with 2 $fb^{-1}$ (Run IIa) the Tevatron experiments will be able to exclude SM Higgs at 95% CL for masses up to 120 GeV. With 10-15 $fb^{-1}$ it will be possible to extend the reach up to about 180 GeV. It was also concluded that experimental observation of the SM Higgs boson at $5\sigma$ level may require significantly larger statistics and that CDF and D0 will have to combine their results in multiple search channels.

## 3 CDF Searches for MSSM Higgs Bosons

Numerous theoretical attempts to extend the SM (see review in [6]) usually lead to the introduction of at least one additional doublet of scalar fields in the Higgs sector. In the framework of minimal supersymmetric extention of the Standard model (MSSM) this results in 5 Higgs boson mass eigenstates - 3 neutral (h/H/A) and 2 charged ($H^+$ and $H^-$). Instead of one parameter - the mass of the Higgs boson - the phenomenology is now described by the 2 parameters with the most popular choice for which being $\tan\beta$ and mass of the pseudoscalar neutral boson $M_A$. Interesting new feature of the MSSM is that the couplings of the MSSM Higgs bosons to fermions may be enhanced by a factor of about $\tan\beta$ , which puts the model within the reach of LEP and the Tevatron Run I experiments.

### 3.1 Search for the Neutral MSSM Higgs

Exploring the area of large $\tan\beta$ CDF searched for the neutral MSSM Higgs boson in the channel $p\bar{p} \rightarrow H\, b\bar{b} \rightarrow b\bar{b}\; b\bar{b}$ ( [7]). As production of the Higgs boson would manifest itself as an excess of events with 4 b-jets, the selection procedure required an event to have 4 jets with $E_t$ >15 GeV and $|\eta|$<2.1. To optimize sensitivity 3 jets out of 4 were required to be B-tagged. Major background in this channel comes from QCD processes, the area in $\tan\beta : M_A$ space excluded by the search is shown in Fig.4 (left)

### 3.2 Search for the Charged Higgs

As the SM doesn't include any charged scalar bosons, experimental observation of the charged Higgs would immediately exclude it. In case $H^+$ mass is less than the mass of the top quark, it could be produced in the decays of top quark t $\rightarrow$ $H^+$b. At large $\tan\beta$ the dominant $H^+$ decay channel is $H^+ \rightarrow \tau\nu$ and production of the charged Higgs in top decays would lead to the excess of events with energetic isolated $\tau$ leptons, large $\not{E}_{\mathrm{T}}$ and B-jets. Under these assumptions, CDF collaboration performed searches for the charged Higgs production in top decays ([8]). Using Run I data sample of 100 pb$^{-1}$ CDF excluded at 95% CL area in the $\tan\beta$ : $M(H^+)$ plane shown in Fig.4(right).

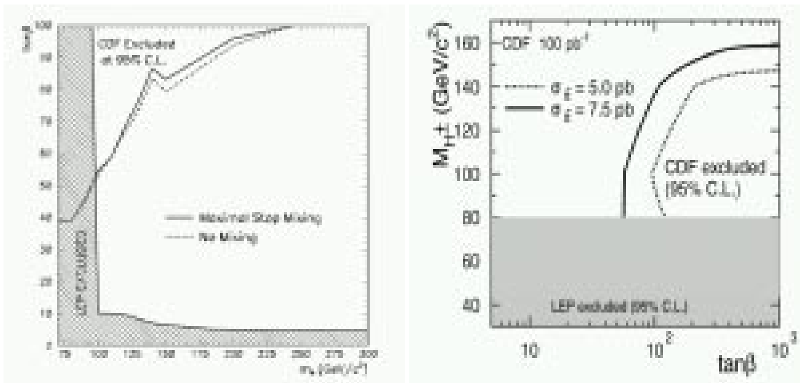


Figure 4. Left: area in $\tan\beta$ : $M_A$ plane excluded at 95% CL by the CDF search for the neutral MSSM Higgs boson ( [7]) Right: area in $\tan\beta$ : $M(H^+)$ plane excluded at 95% CL by the CDF searches for charged Higgs ( [8] )

### 3.3 MSSM and Detection of the $\tau$-leptons

At large $\tan\beta$ MSSM phenomenology is significanly different from the "traditional" area of $\tan\beta \approx 1$. Decays of the supersymmetric particles, including decays of the neutral and charged Higgs bosons could result in the final states with the excess of $\tau$ leptons, which emphasizes importance of their experimental detection. In particular, triggering on $\tau$ leptons becomes a priority. In Run II CDF has implemented a set of single $\tau$ and di-$\tau$ triggers [9], $W \rightarrow \tau\nu$ signal observed using $\tau - \not{E}_{\mathrm{T}}$ trigger is shown in Fig. 5.

## 4 Summary

Experimental search for the Higgs boson is one of the most scientifically important goals of Tevatron experiments. In Run I CDF experiment performed searches for the SM Higgs boson in various final states and although experimental sensitivity of Run I was not enough to discover the SM Higgs, a

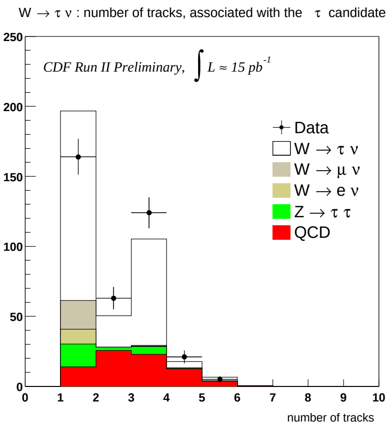


Fig 5: Charged track multiplicity for $W \to \tau\nu$ candidate events

number of important experimental search techniques has been established. In preparations for Tevatron Run II CDF detector has undergone major upgrade and its potential for Higgs discovery has greatly increased. Run II operations started in July'2001 and so far CDF has collected 70 $\mathrm{pb}^{-1}$ of data. With the improved Tevatron performance we expect to start exploring limits of MSSM Higgs physics in the year of 2003.

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